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$GaInP_2$/GaAs TANDEM CELLS FOR SPACE APPLICATIONS

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The monolithic, tunnel-junction-interconnected tandem combination of a $GaInP_2$ top cell and a GaAs bottom cell has achieved a one-sun, AM1.5 efficiency of 27.3%. With proper design of the top cell, air mass zero (AM0) efficiencies greater than 25% are possible. A description and the advantages of this device for space applications are presented and discussed. The advantages include high-voltage, low-current, two-terminal operation for simple panel fabrication, and high conversion efficiency with low-temperature coefficient. Also, because the active regions of the device are aluminum-free, the growth of high efficiency devices is not affected by trace levels of O_2 or H_2O in the metal organic chemical vapor deposition (MOCVD) growth system. While this study focuses on material grown on GaAs substrates, the device is probably adaptable to growth on Ge substrates. Encouraging preliminary radiation resistance data are presented in a companion paper.

INTRODUCTION

The basic requirements for space solar cells are high efficiency at elevated temperatures, high power-to-weight ratio, and resistance to the damaging effects of low orbit radiation. The $GaInP_2$/GaAs monolithic, two-terminal tandem solar cell, invented and developed at SERI (Olson, 1985), has a good chance of meeting these requirements. In the following sections, we briefly review the previous work in this area, describe the design of an AM0 version of the $GaInP_2$/GaAs tandem cell, examine some of the advantages and disadvantages of the device, and give a brief overview of the tunnel junction interconnect.

$GaInP_2$/GaAs TANDEM SOLAR CELL

A schematic diagram of the $GaInP_2$/GaAs monolithic cascade cell is shown in Fig. 1. The structure was grown in a vertical, air-cooled reactor at one atmosphere using MOCVD, the detailed aspects of which are described elsewhere (Olson, 1986; Olson, 1987). The Group III source gases were trimethyl indium, trimethyl gallium, and trimethyl aluminum; the Group V source gases were arsine and phosphine. The dopant sources were diethyl zinc (DEZ) and hydrogen selenide. The arsine and phosphine were purified on line by passing them over a gettering compound supplied by Advanced Technology Materials, Inc. The optoelectronic properties (Kurtz, 1988) and photovoltaic quality (Olson, 1987) of the materials listed above are complex and coupled functions of the growth temperature (T_g), V/III ratio, composition, dopant type and concentration, and substrate quality. Generally, however, the cascade device was grown at T_g = 700 °C. The phosphides were grown with V/III = 30 and growth rate = 80-100 nm/min; the arsenides, with V/III = 35 and growth rate = 120-150 nm/min, except that the GaAs tunnel diode was grown at a rate of 40 nm/min.

The absorbers of both subcells were doped with Zn to a level of 1-4 x 10^{17} cm^{-3}. The emitters and window layers were doped with Se at about 10^{18} cm^{-3}. Both layers of the GaAs tunnel diode were heavily doped at concentrations approaching 10^{19} cm^{-3}.

The post-growth processing of these devices is very similar to that used for single-junction GaAs cells. The front and back contacts to all the devices reported here were electroplated with gold. Because of the high dopant concentration in both the GaAs substrate and the top GaAs contacting layer (not shown in Fig. 1), no thermal annealing of either contact was required. The front contact was defined by photolithography and obscured approximately 5% of the total cell area. The cell perimeter was also defined by photolithography and a mesa etch that uses a sequential combination of concentrated hydrochloric acid and a dilute ammonia:peroxide:water solution. The ammonia/peroxide solution was also used to remove the GaAs contacting layer between the gold grid fingers. The antireflection coating was a double layer of evaporated ZnS and MgF_2, with thicknesses of 65 and 120 nm, respectively.

The cell efficiency was measured using the multisource simulator method of Glatfelter and Burdick (1987). The simulated solar spectrum was adjusted using two reference cells. One reference cell was a $GaInP_2$ top cell; the other was a GaAs cell coated with the GaAs tunnel junction and a layer of $GaInP_2$ to simulate the optical transmission to the GaAs bottom cell in the actual tandem device. The spectrum of the simulator was adjusted with filters until both reference cells produced the correct (ASTM) standard E892-87 global, short-circuit current at 1000 W/cm^2. Using this spectrum, the current of the cascade cell was then measured.

The best efficiency (at one sun, AM 1.5) measured to date for this device is 27.3% (Olson, 1990). The light IV curve of this device is shown in Fig. 2. The short-circuit current density (J_{sc}), open circuit voltage, (V_{oc}), and fill factor (FF), are 13.6 mAcm^{-2}, 2.29 V, and 0.87, respectively. The area of this device is 0.25 cm^2, and the band gap of the top cell is 1.85 eV. This is the highest efficiency reported for a two-terminal, tunnel-junction-interconnected tandem photovoltaic device, and it represents a significant improvement with respect to our previously reported work (Olson, 1985; Olson, 1987). Chung et al. (1989) have reported a 27.6% efficient monolithic AlGaAs/GaAs solar cell. This device has a metal (as opposed to a tunnel-junction) interconnect and includes a prismatic cover slip to eliminate the photocurrent loss associated with grid shadowing. In our case, the prismatic cover slip would boost the efficiency from 27.3% to 28.7%.

Numerous factors affect the efficiency of these multijunction solar cells. They include the electronic quality of the top and bottom cell materials, the band gap and thickness of the top cell, the design of the anti-reflection coating (ARC), the tunnel junction interconnect, and the thickness and passivating properties of the window layers.

The $GaInP_2$/GaAs tandem cell just described had a thin $GaInP_2$ top cell designed for current-matched, optimum performance under a AM 1.5 global spectrum. Under an AM0 spectrum (and for all series connected tandem cells in general), a significant potential loss mechanism is associated with current matching between the top and bottom cells. The top and bottom cell currents (J_T and J_B) are determined primarily by the band gaps of the top and bottom cell materials. It was assumed in previous treatments of this problem that the subcells were infinitely thick and that quantum efficiencies were equal to 100%. With these assumptions, for a bottom-cell band gap of 1.42 eV, the optimum top-cell band gap for an AM0 solar spectrum is 2 eV. Because the nominal band gap of $GaInP_2$ is 1.9 eV, we expect that $J_T > J_B$ for a thick, high-quality $GaInP_2$ top cell on a GaAs bottom cell. Furthermore, the band gap of MOCVD-grown $GaInP_2$ can be as low as 1.82 eV, depending on growth conditions (Kurtz, 1990), exacerbating this problem. This anomalous change in band gap appears to be related to changes in the short- or long-range site order of Ga and In on the Group III sublattice. For top-cell material with a low band gap, the solution to this problem is to reduce the thickness of the top cell. A calculation of the expected effect is shown graphically in Fig. 3 (Kurtz, 1990). Plotted in Fig. 3a are the efficiencies of a series-connected tandem cell with infinite and optimized top-cell thicknesses as a function of the band gap of the top cell for a GaAs (1.423 eV) bottom cell. In Fig. 3b, we plot the optimum top cell thickness as a function of the top-cell band gap. All of these calculations assume no external losses and unity internal quantum efficiencies. For top-cell band gaps greater than 2 eV, $J_T < J_B$ and current matching is not achievable. For top cell band gaps from 1.84 to 1.9 eV, the current-matched top-cell thickness varies from 500 to 700 nm and the AM0 efficiency varies from 30.8% to 31.5%. For a top-cell band gap of 2 eV, the maximum efficiency is 32.4%. Therefore, it is apparent that substantial changes in the top-cell band gap can be accommodated with only minimal loss in the tandem cell efficiency.

ADVANTAGES

The $GaInP_2/GaAs$ tandem cell has several advantages for space applications as compared to GaAs and InP single-junction cells and AlGaAs/GaAs, GaAs/Ge, InP/GaInAs, and GaAs/GaSb tandems. Table 1 lists the present AM0 efficiency of a nonoptimized $GaInP_2/GaAs$ tandem cell with the predicted efficiency of an optimized tandem cell. The predicted beginning of life (BOL) efficiency is 26.1%. The present AM0 performance is from cell parameters all taken from one device that was not current matched for AM0. The largest deficiency between present and predicted performance are for the parameters V_{oc} and J_{sc}. The V_{oc} for the present device is low because of losses associated with a high interface recombination velocity at the back of the $GaInP_2$ top cell (80-100 meV) and an anomalous loss of voltage for bottom cells coated with a tunnel junction and a $GaInP_2$ top cell. Both of these problems have recently been solved and the combined V_{oc} of separate top and coated bottom cells is now 2.41 V. Another 20 mV is expected with further improvements in the top cell. The predicted J_{sc} is one-half of 34 mA/cm^2 (an extrapolation of the AM1.5 J_{sc} predicted by Tobin, et al. (1990), less 0.3 mA/cm^2 for absorption losses associated with the GaAs tunnel junction interconnect (vide infra). The predicted BOL efficiency of 26.1% is a 15% improvement over a comparable single-junction GaAs cell with a J_{sc} of about 34 mA/cm^2 and a predicted efficiency of 22.7%. It would appear at this time that the achievement of 26.1% does not require any major technological breakthroughs or advances.

Besides efficiency, the $GaInP_2/GaAs$ tandem cell has numerous advantages over the other multijunction devices. With a tunnel-junction interconnect, it is a true monolithic, two-terminal device that does not require a prismatic cover slip to compensate for the excess obscuration of a metal interconnect. As a two-terminal device, it should also be easier to assemble into modules than the three- and four-terminal devices. Using a tunnel-junction interconnect also makes post-growth processing of the device similar to that of a single-junction device and considerably easier than that of a three- or four-terminal device.

The choice of top and bottom cell band gaps also has a major effect on the efficiency, temperature coefficient, and I^2R losses in the cell. The efficiency of the $GaInP_2/GaAs$ tandem cell has a temperature coefficient similar to that of the bottom GaAs cell and not much different than that of a four-terminal $GaInP_2/GaAs$ tandem structure, as shown in Fig. 4. For these calculations, band gaps of 1.424 and 1.9 eV were used for the GaAs and $GaInP_2$, respectively. Except for the AlGaAs/GaAs tandem cell, all of the other tandem cells listed here have a low-band-gap bottom cell and, hence, a much larger temperature coefficient. The cell current is determined by the top-cell band gap. The cell current will be a factor of two lower, and the associated I^2R losses (for a given cell resistance) will be a factor of four lower, than those of InP/GaInAs or GaAs/GaSb tandem cells. These factors are particularly important for concentrator applications, where the cell is run at elevated current and temperature.

It would appear from preliminary experiments that the $GaInP_2/GaAs$ tandem cell, like GaAs, can be grown on germanium substrates. It should also be compatible with the (CLEFT) technology. These technologies can significantly increase the power-to-weight ratio of this device as compared to the other tandem cell structures.

Compared to the AlGaAs/GaAs tandem cell, the $GaInP_2/GaAs$ tandem cell contains no Al in the active regions of the device. (Aluminum is used in window layers where material quality is less critical.) Because of the strong affinity between Al and O_2 and H_2O, growing high-quality AlGaAs is difficult if not impossible in most systems. This is very important from the standpoint of yield and manufacturability. It also means that one can generally use lower growth temperatures than those used for AlGaAs. On the other hand, $GaInP_2$ has been viewed as a material that is also difficult to grow. Its composition must be precisely controlled; there are anomalous changes in its band gap with growth conditions; and there difficulties associated with the chemistry of trimethyl indium and PH_3. However, all of these problems are manageable and well understood, and numerous laboratories around the world have abandoned 1.9 eV AlGaAs and are growing $GaInP_2$ laser and LED devices with MOCVD.

Finally, it appears that because of the thin top cell (and other phenomena that are not well understood) the $GaInP_2$/GaAs tandem cell can be designed to be relatively radiation resistant, with an end-of-life efficiency (10^{15} 1 MeV electrons/cm^2) close to 21%. This aspect of the problem is discussed further in a companion paper in this volume (Kurtz, 1991).

TUNNEL JUNCTION INTERCONNECTS

The main issues for tunnel-junction interconnects are (1) absorption losses of light destined for the bottom cell, (2) the series resistance and peak tunneling current, and (3) effects associated with the required heavy doping. There are two ways to minimize absorption losses: (1) fabricate the tunnel junction in a semiconductor with a band gap that is greater than or equal to that of the top cell (this may not always work because of incomplete absorption of all super-band-gap light in the top cell and/or sub-band-gap absorption of light in the degenerately doped tunnel junction), or (2) reduce the thickness of the tunnel junction. The peak tunneling current is an exponential function of the band gap of the material. Therefore, for tandem cells with high-band-gap top cells like $GaInP_2$, it is better to employ the second approach and use, in our case, a thin GaAs tunnel junction for the interconnect. From calculations similar to those of Kurtz, et al. (1990), modeling the absorption of light in degenerately doped GaAs, we have shown that the current loss to the bottom GaAs cell per unit thickness of the GaAs tunnel junction is about 0.01 mA/cm^2/nm. A 30-nm-thick GaAs tunnel junction will reduce the tandem cell current by less than 2%.

The series resistance and peak tunneling current are complex functions of the dopant type and concentration, interdiffusion, memory effects, and homogeneous and heterogeneous reaction chemistry. Contrary to the popular lore, an adequate tunnel junction can be fabricated in GaAs with the dopants Zn and Se. A solar concentration of 1000x requires a peak tunneling current of greater than 14 A/cm^2. Peak tunneling currents of 60 A/cm^2 have been achieved with Se and Zn, albeit with low yield, at a growth temperature of 600°C. The yield increases significantly at a growth temperature of 650°C with a peak tunneling current of 42 A/cm^2. The major problem with these devices is the spillover of the dopants into top cell. This problem is caused mainly by the large memory effects that are normally associated with these dopants. Silicon from Si_2H_6 and C from CCl_4 were studied as alternatives for Se and Zn, respectively. Both of these dopant sources are known to exhibit negligible memory effects. When C is substituted for Zn, peak tunneling currents in excess of 100 A/cm^2 were achieved after optimization, still the memory problems with Se persist. When Si and C are substituted for Se and Zn, there are no memory problems, but the best tunnel junctions made so far, while suitable for one-sun operation, will dominate the series resistance of the device for concentrations around 500x. In the course of this work, we also discovered that C appears to form a deep level (in addition to a shallow acceptor) in $GaInP_2$ and would therefore not be a suitable dopant for the base layer of the top cell (Kibbler, 1991). More work must be done to fully optimize these tunnel junctions.

SUMMARY

In summary, we have reviewed the previous work in designing and operating $GaInP_2$/GaAs tandem solar cells for terrestrial systems. We show that this device technology is easily adaptable to space PV applications and has numerous advantages over other single-junction and multijunction solar cells. These advantages include a projected AM0 efficiency close to 26% with a low cell current, a low temperature coefficient, and a relatively high tolerance to the effects of radiation. The materials are generally well understood, and their growth is compatible with large-scale deposition on lightweight substrates such as germanium.

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Table 1. Present and Predicted AM0 Performance of $GaInP_2/GaAs$ Cells

Cell Parameters	Present	Predicted
V_{oc} [V]	2.3	2.43
J_{sc} [mA/cm^2]	16.1	16.7
ff	0.87	0.88
AM0 Efficiency [%]	23.6	26.1

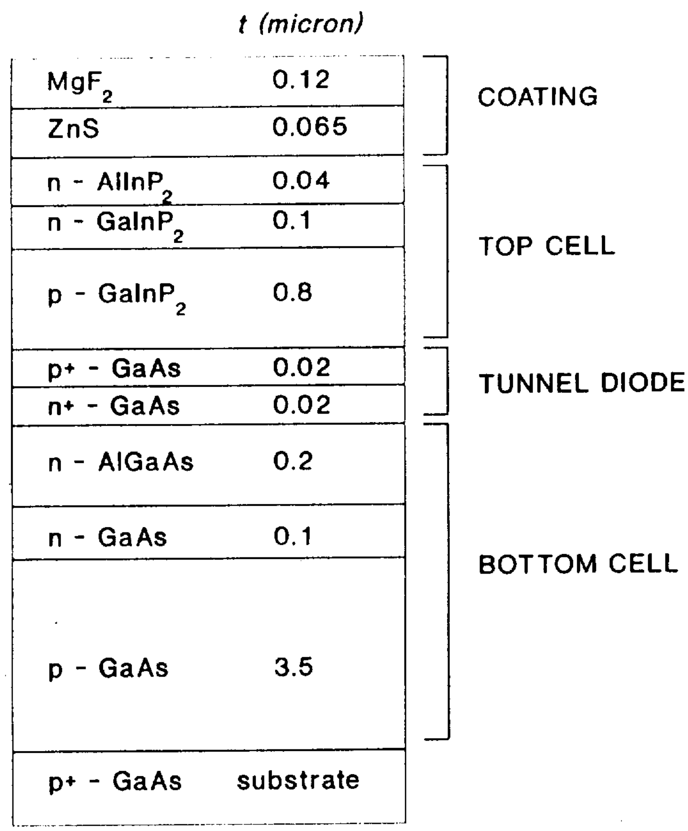

Fig. 1. A schematic cross-section of the $GaInP_2/GaAs$ tandem cell. A GaAs contacting layer, antireflection coating, and metallization are not shown.

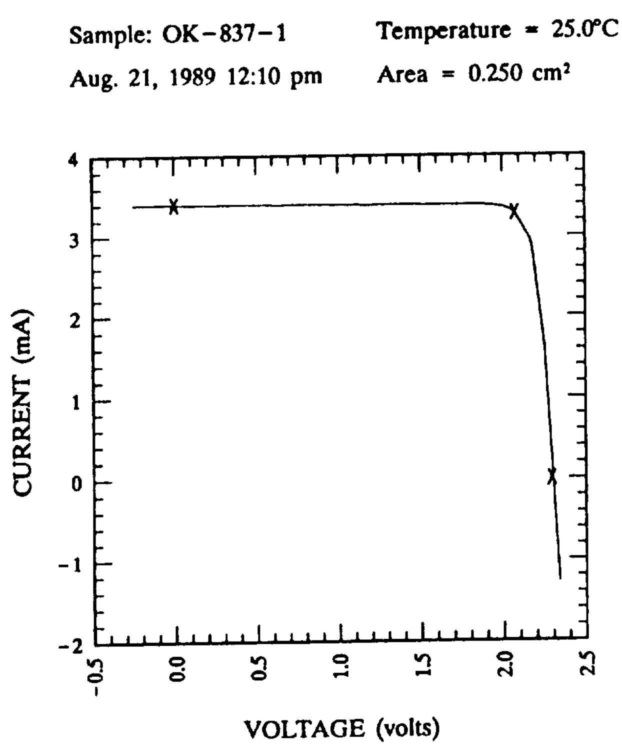

Fig. 2. Light IV curve of a 27.3%-efficient (AM1.5), two-terminal $GaInP_2/GaAs$ tandem solar cell.

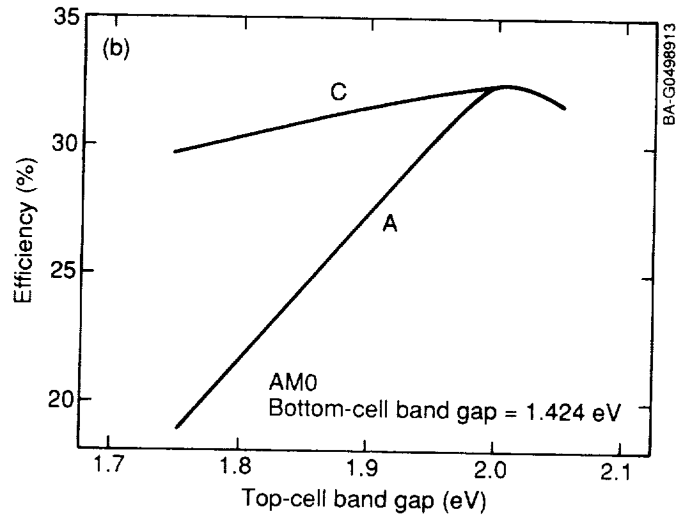

Fig. 3a. Modeled AM0 tandem-cell efficiency, assuming no losses, as a function of the top cell band gap with a thick (Curve A) and optimally thin top cell (Curve C). The efficiency for Curve C assumes zero recombination velocity at the interface between the top cell and the tunnel-junction interconnect.

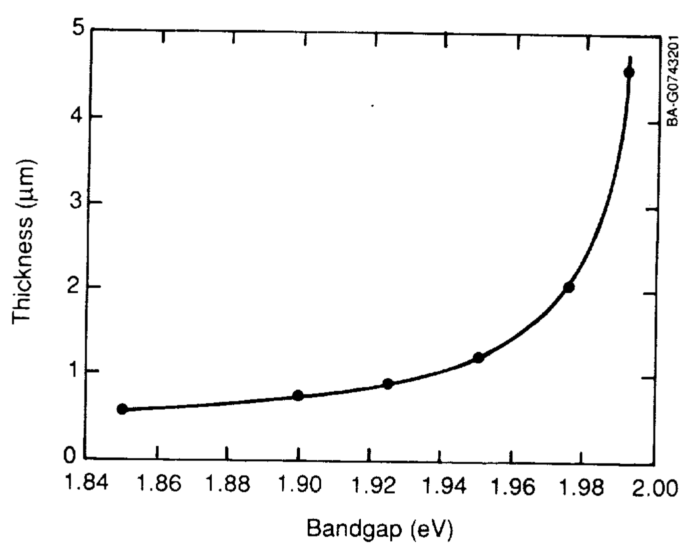

Fig. 3b. Optimal top cell thickness as a function of top cell band gap. The bottom cell is GaAs with a band gap of 1.424 eV.

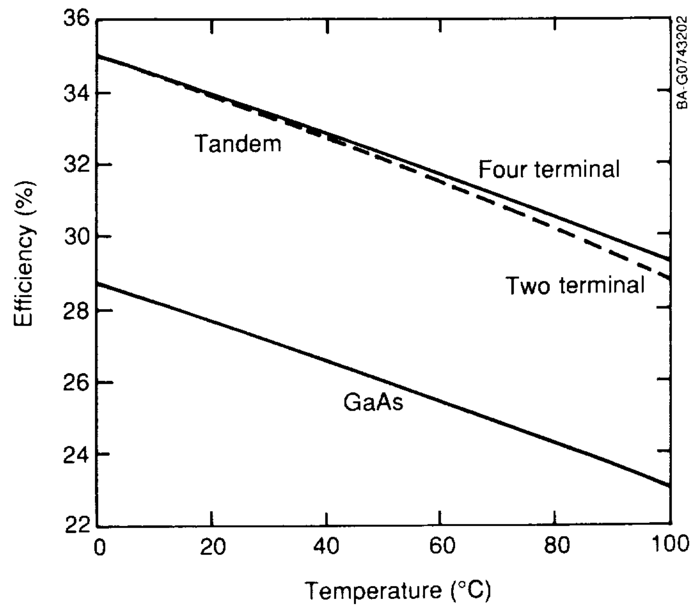

Fig. 4. Modeled cell efficiency (AM0) as a function of cell temperature for a single-junction GaAs cell and series- and separately connected $GaInP_2$/GaAs tandem cells. These are ideal efficiencies with no losses.